Description and Investigation of Size Effects in the Scaling of a Hot Forging Process into the Microscale

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Abstract
The application of metal forming technologies to the production of metallic microparts is limited by problems arising from size effects related to these small dimensions. An approach to these problems is the laser-assistance of the microforming process. Laser light is used to increase the temperature of the material during forming, to increase the formability in the required area of the part and to reduce the flow stress and anisotropy of the material. To enable the transmittance of laser light into the workpiece, sapphire tools are used. Experimental investigations have shown that the use of sapphire tools in laser-assisted microforming processes is a suitable method for the production of microparts. Further investigations aim at modelling the material behaviour and size effects in microforming processes and the integration of these models into FE simulations in order to extend its application to microproduction processes.

Keywords:
Laser, forming, size effects

1 INTRODUCTION

From the general trend towards higher miniaturization and functional integration results an increasing demand for metallic parts or structures of smallest dimensions (down to 100 µm) like miniature springs and screws, connector pins, shafts or gears. Industrial realization of these parts and the further breakthrough of products containing microparts require suitable production technologies with respect to accuracy, productivity, efficiency and reliability. This aspect is still a significant limitation [1,2].

The production processes of microsytem technology like LIGA and etching are either not suitable for processing metals like steel or the productivity is low. Despite the advances in the downscaling of several classical production technologies like cutting to laser machining these are still far from being established in the production for microparts [3,4].

Metal forming offers the advantages of high production rates, minimal or zero material loss, excellent mechanical properties of the product and small tolerances making it suitable for mass production and near net shape technology. But the application of metal forming technologies to the production of microparts is still limited as a series of problems arise in scaling down this technology to the microscale.

2 SIZE EFFECTS IN MICROFORMING

In this paper microforming is understood as metal forming of parts or structures with at least two dimensions in the sub-millimetre range in accordance to [2]. In this range “size effects” occur, which lead to a different process behaviour compared to conventional dimensions. This results from the fact that some factors like the microstructure of the material or the surface topology and roughness are nearly independent of the dimension of the part to be produced and therefore cannot be scaled down in the same way as the geometry. Size effects in the frictional and the material behaviour appear to be the main factors in microforming. Thus the influence of the microstructure becomes one of the most important aspects to consider.

With decreasing size the influence of single grains and their orientation has to be taken into account, especially when only few grains are present in one dimension [2,5,6]. Anisotropy and texture of the material are further parameters to be considered. An increasing variation in the material behaviour has been observed, leading to reduced process stability and reliability.

3 LASER-ASSISTED MICROFORMING

The importance of the microstructure in microforming has been pointed out. An approach to compensate for or reduce the impact of size effects is to influence the microstructure during the forming process. This can be accomplished by heating the workpiece. At high temperatures an increased formability is achieved while the flow stress and thus process forces are reduced as more slip systems are activated. This reduces the anisotropic material behaviour resulting in a more homogeneous forming with improved reproducibility [7,8].
For the purpose of heating the material during the microforming process laser radiation seems the most suitable choice as it offers main advantages with respect to other methods:

- The laser energy input and thus the resulting temperature in the workpiece, can easily be controlled via the current of a diode laser.
- Local heating of selected areas of the workpiece is possible, allowing to limit the heating to the forming zone.
- Needed temperature gradients can be achieved by control of laser power.
- The absorption of laser radiation allows short process times which cannot be accomplished with heat transfer from pre-heated tools.
- Reaching different materials properties by controlling the cooling down velocity with control of laser power.

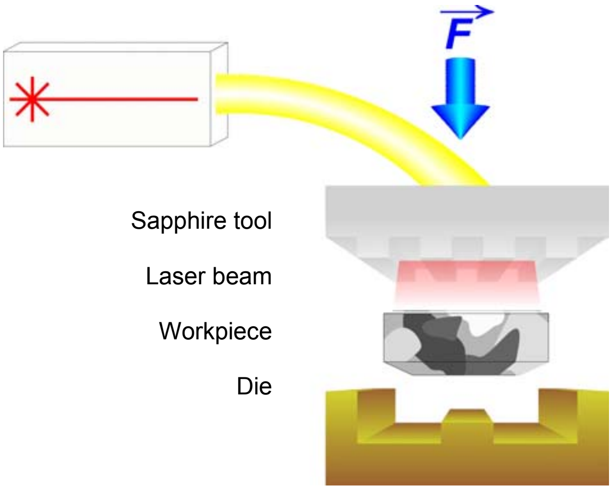


Figure 1: Principle of laser-assisted microforming.

The proposed method (Figure 1) requires transparent tools in order to allow the transmittance of the laser light to the forming region. Sapphire combines the required transparency to laser radiation (at wavelengths λ > UV) with excellent mechanical properties like high hardness, compressive strength and Young's Modulus, making it suitable for metal forming. In addition its melting temperature of 2050 °C allows warm respectively hot forming of steel without destroying the tool.

4 EXPERIMENTAL SET-UP FOR LASER-ASSISTED MICROFORMING

The application of metal forming technologies to the production of microparts requires suitable production systems with high accuracy and productivity. These requirements pose serious difficulties to the technical implementation of the clamping of the tools and workpiece. The laser-assistance of the forming process requires the integration of the laser optics into the tool system. The laser optics should be in a short distance of the sapphire tool in order to achieve a small laser spot and reduce losses in laser power. This leads to conflicting demands as high stiffness and mechanical strength are needed in order to transmit the process forces of several 1000 N while meeting the desired accuracy of positioning.

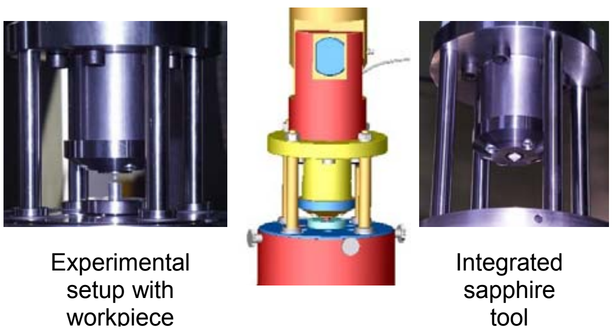


Figure 2: Prototype of a setup for laser-assisted microforming.

A prototype of an experimental setup for laser-assisted microforming (Figure 2) has been developed at the Laboratory of Production Engineering of the University of the Federal Armed Forces Hamburg which accounts for these requirements. In order to improve the accuracy of the tool positioning a new guiding system was implemented which is independent of the guiding of the machine into which this apparatus is integrated. The setup is build in a modular conception allowing to exchange workpiece and tool carriers for different applications. The laser optics are integrated into the tool carrier system. The distance to the tool and workpiece is adjustable. The laser system includes a diode laser package with a maximum output power of 20 W and a wavelength of 809 nm as well as an aiming beam for the purpose of alignment of the laser beam.

5 EMBOSSING EXPERIMENTS WITH SAPPHIRE TOOLS

Embossing experiments have been carried out for the verification of the applicability of microforming with sapphire tools. Previous experiments have shown that structures as small as 100 µm can be reproduced in aluminium. The punch with a prototype structure of rectangular shapes as well as the imprint in Al99.5 are shown in Figure 3.

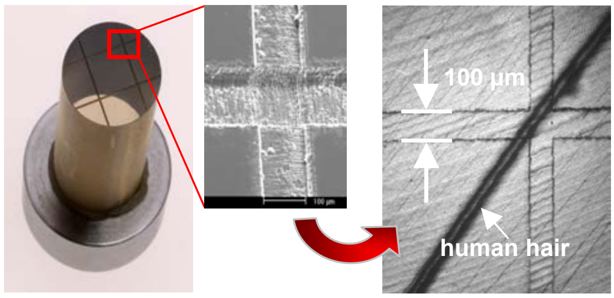


Figure 3: Prototype of a sapphire tool for embossing and imprint in aluminium in comparison with a human hair.

Equivalent experiments with harder materials like steel are a current object of research. Embossing experiments were carried out with workpieces of stainless steel (1.4301). Figure 4 shows the punch with structures of cylindrical shape. The inner hole measures about 400 µm in diameter while the ring has a width of about 250 µm. The depth of the structures is 250 µm.

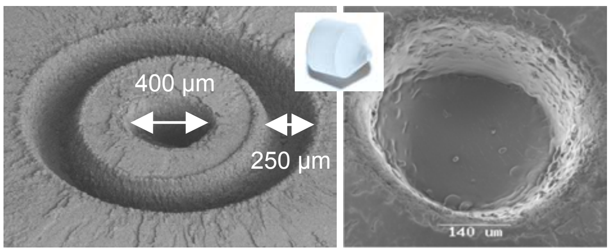
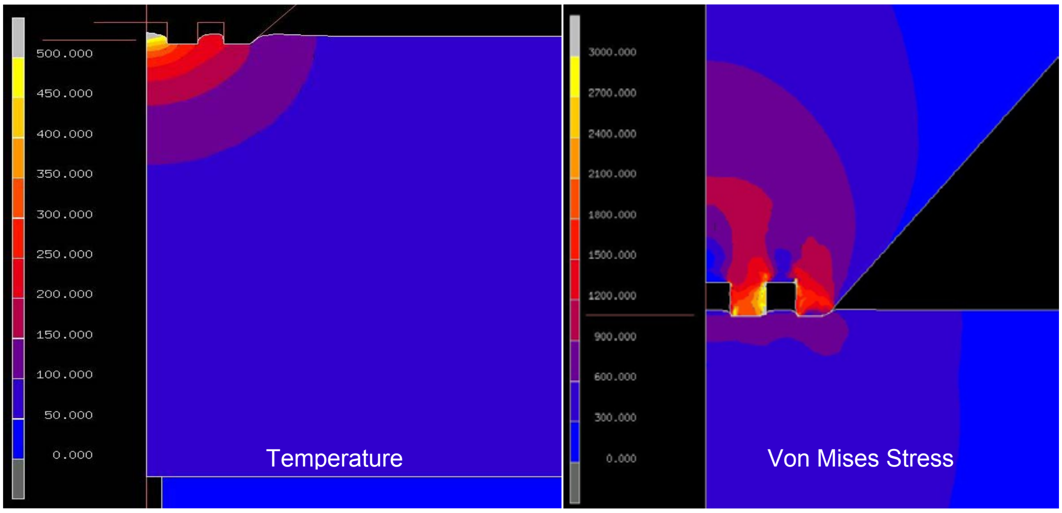


Figure 4: Sapphire tool for embossing experiments.

A summary of the experimental conditions is given in Table 1. The maximum force applied was limited to 5000 N because of the risk of rupture of the brittle sapphire tools. Experiments with and without laser-assistance of the forming process were carried out in order to assess the advantages of this technique. In order to maximize the absorbed laser power, the workpiece was coated with graphite which also acts as a lubricant. The influence of the graphite on the process result was also to be assessed.

Test series	Number of workpieces	Workpiece dimensions	Workpiece surface	Max. force applied	Laser parameters
A	5	Ø 10 x 5 mm	blackened with graphite	5000 N	20 W laser output power
B	5	Ø 10 x 5 mm	blackened with graphite	5000 N	Laser off
C	5	Ø 10 x 5 mm	original surface	5000 N	Laser off

Table 1: Parameters of the embossing experiments in stainless steel 1.4301 (X5 CrNi 18 10).



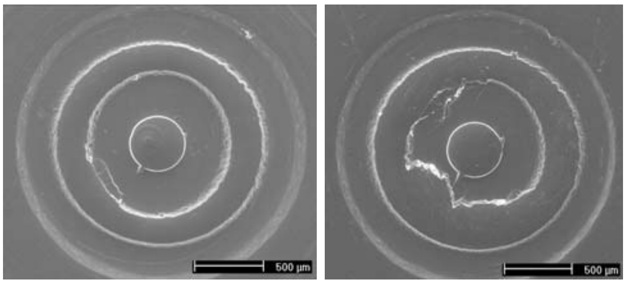
(a) (b)

Figure 5: Results of FE simulations of the embossing experiments.

Previous experiments showed that the absorption of the laser radiation can be increased by coating the workpieces with graphite (from about 40% to more than 65%). Further improvements have to be achieved as this is still unsatisfactory and further losses occur, e.g. in the laser optics and in the sapphire tool due to reflection and absorption. The experimental results and FE simulations (Figure 5 (a)) show that this is a major problem as the temperature in the forming zone is too low (T = 150-300°C) to achieve significant improvements by the laser-assistance of the forming process in comparison to cold forming. Following solutions are suggested for further experiments:

- Integration of materials with low heat conductivity (e.g. zirconia oxide) into the workpiece carrier system in order to reduce the heat transfer from the workpiece into adjacent parts, to reach higher temperature in the workpiece,
- Integration of materials with high heat conductivity (e.g. aluminium) into the workpiece carrier system in order to arise the heat transfer from the workpiece into adjacent parts, to get greater temperature gradients in the workpiece,
- Application of anti-reflex coatings on the sapphire tool,
- Testing of different coatings of the workpiece in order to improve absorption,
- Application of lubricant coating with high transmission and low heat conductivity to keep heat flow between workpiece and sapphire small,
- Use of laser sources with higher output power.

SEM images of imprints in stainless steel are shown in Figure 6. The depth of the imprints is about 100 µm, showing no significant differences between the experiments with (Figure 6 (a)) or without laser-assistance of the process (Figure 6 (b)) due to the insufficient heating of the workpiece. The process forces were not high enough to achieve a sufficient filling of the cavities of the tool. This emphasizes the importance of achieving high temperatures in order to reduce the process forces and improve the quality of the results. While this shows the limitations of microforming of stainless steel at lower temperatures, softer materials like aluminium can be processed (cp. Figure 3).



(a) (b)

Figure 6: Results of the embossing experiments: imprints in stainless steel 1.4301.

In the imprints (Figure 6) the fracture of the sapphire tool and the progress of the breakage can also be observed. First signs of damage of the tool could already be detected after few experiments (Figure 6 (a)). Figure 7 shows the fractured sapphire tool. Nearly the whole surface of the ring structure in the centre is damaged and partially pulverized after 17 forming experiments, emphasizing the importance of reducing the process forces. The SEM image on the right exhibits further material loss of the damaged tool due to later ultrasonic cleaning.

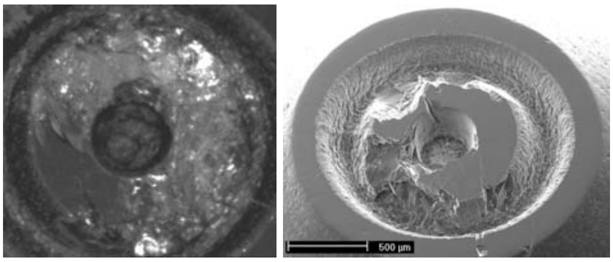


Figure 7: Sapphire tool fractured during the embossing experiments.

This discloses a main problem in the utilization of a brittle material like sapphire for metal forming tools. The nominal pressure on the contact area of the tool surface was 2500 N/mm^2, less than the compressive strength of sapphire (3000 N/mm^2). But the stresses acting on the edges of the tool may exceed this value (Figure 5 (b)) causing the fracture of the brittle material which is very sensitive to tensile stresses. These lead to crack initiation and to a breakage of the tool.

In this context microcracks, which are induced on the surface of the structure during the profiling process (ablation with excimer laser), have to be accounted for. Also small manufacturing errors of the tool and its clamping can lead to an asymmetric force distribution during the pressing process which induces tensile stresses [9]. The inaccuracies based on the experimental set-up tolerances in respect of parallelism of the tool and workpiece surfaces are reasons for asymmetric force distribution in the tool. The inaccuracies based on the experimental set-up tolerances in respect of positioning the Sapphire to the workpiece and leading the sapphire during pressing into the workpiece can also cause asymmetric force distribution in the sapphire.

6 SIMULATION OF HEATING STRATEGIES

For laser-assisted microforming the temporally heating characteristics of the workpiece are of primary importance. The temporally heating characteristics affect the workpiece temperature, the form filling of the workpiece into the die, the tool load and the required force of the die. To analyse these dependencies, different heating strategies were simulated in the FE Simulation.

Therefore, in the FE Simulation, the laser energy has been simulated as a heat energy (Figure 8). The simulation shows that laser power of 20 W increases the workpiece temperature (workpiece volume of only a few mm^3) with little temporal retards.

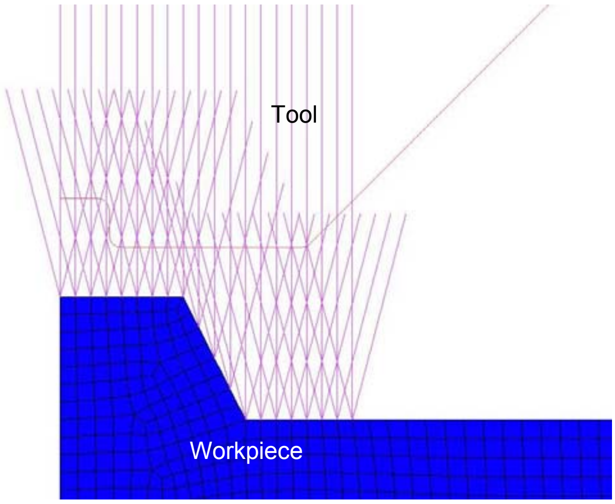


Figure 8: Heat flow simulation in workpiece.

As a result of this dependency the workpiece form filling into the die, the tool strain as well as the force of the die can be managed by control of laser power. Furthermore, it has been noticed that high laser power (Figure 9) should feed the process while high deformation degrees are needed to reach satisfactory form filling of the die (rising temperature of the workpiece decreases the flow stress). These high deformation degrees are normally needed at the end of a forming process.

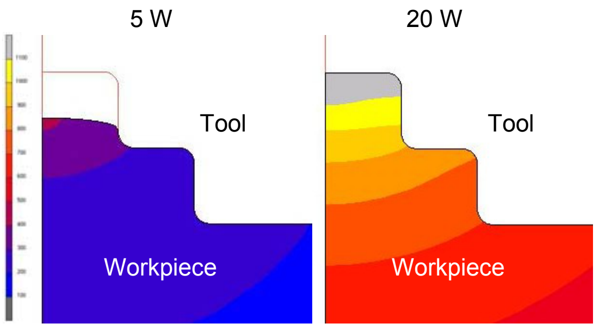


Figure 9: Form filling of the workpiece at different laser power.

To reach high temperature gradients, high laser power should be applied to the forming process in a short time segment. The analyses have figured out that the form filling can be improved by reaching high temperature gradients in the forming process. Figure 10 shows the form filling after a continuous increasing of laser power characteristics into the workpiece. Figure 10 (a) shows a form filling after a short, Figure 10 (b) after a long insertion of laser energy. It is shown that the form filling after a short insertion is better than the form filling after a long insertion even though the inserted laser energy is less with short insertion. This can be explained with rising temperature gradients during forming, when the insertion time is decreasing.

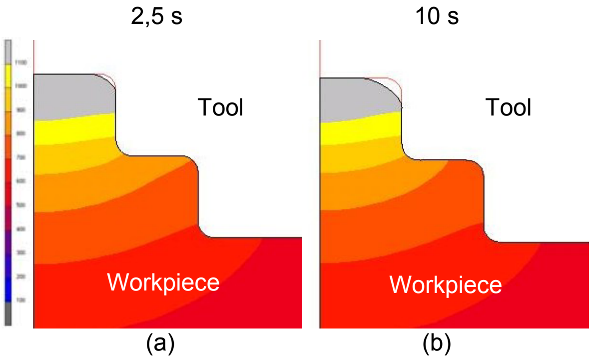


Figure 10: Form filling after fast (left) and slow (right) heating.

To minimise the tool stress it has been noticed, that the maximal laser power and the maximal tool stress should appear at the same time, because at the maximal laser power the temperature is rising and the flow stress is decreasing. That is the reason why the tool stress is decreasing too (Figure 11).

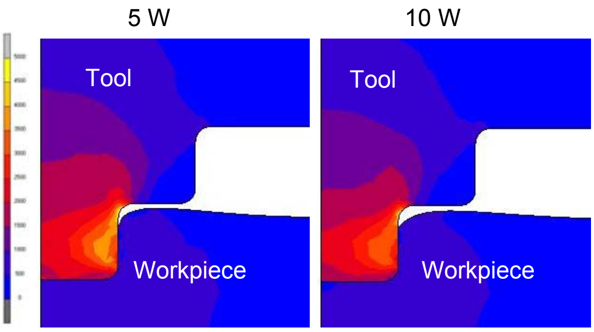


Figure 11: Tool stress at different laser power.

The force of the die also is highly depending on the laser power. With increasing laser power the die force required for reaching a specific distance highly decreases.

7 CONCLUSIONS

Laser-assisted microforming with sapphire tools is proposed for the production of metallic microparts. Sapphire tools meet the requirements for transparency and excellent mechanical properties.

An experimental setup for laser-assisted microforming has been developed and the applicability of the proposed method verified in forming experiments with aluminium. Equivalent experiments with harder materials like stainless steel show the limitations of cold forming for these applications. In embossing the quality of the result is unsatisfactory and the process forces are high, bearing the risk of a fracture of the tool. An approach to overcome these problems is seen in warm and hot forming, e.g. by the proposed method of laser-assisted forming. The optimization of this technique is a current object of research. The heating strategies have been simulated, but need to be verified by trials. Further investigations aim at modelling the material behaviour and size effects in microforming processes. The integration of these models into FE simulations in order to extend the application of this technique to the simulation of microproduction processes is an additional intention.

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